Pion production in NEUT

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Introduction

- Like most generators, NEUT uses a set of separate models to describe the different interactions modes

- Unless otherwise specified, considering NEUT 5.4.0

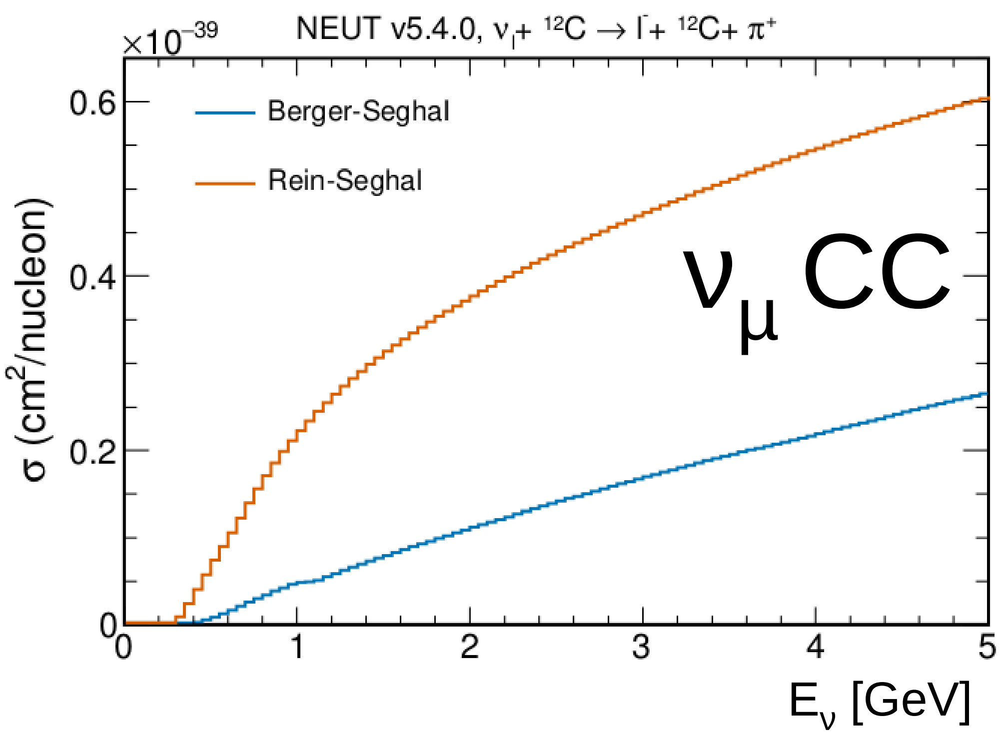
- Will describe the implementation for the different modes producing pions:
  - coherent pion production
  - resonant pion production
  - deep-inelastic, including multi-pion background in the resonance region

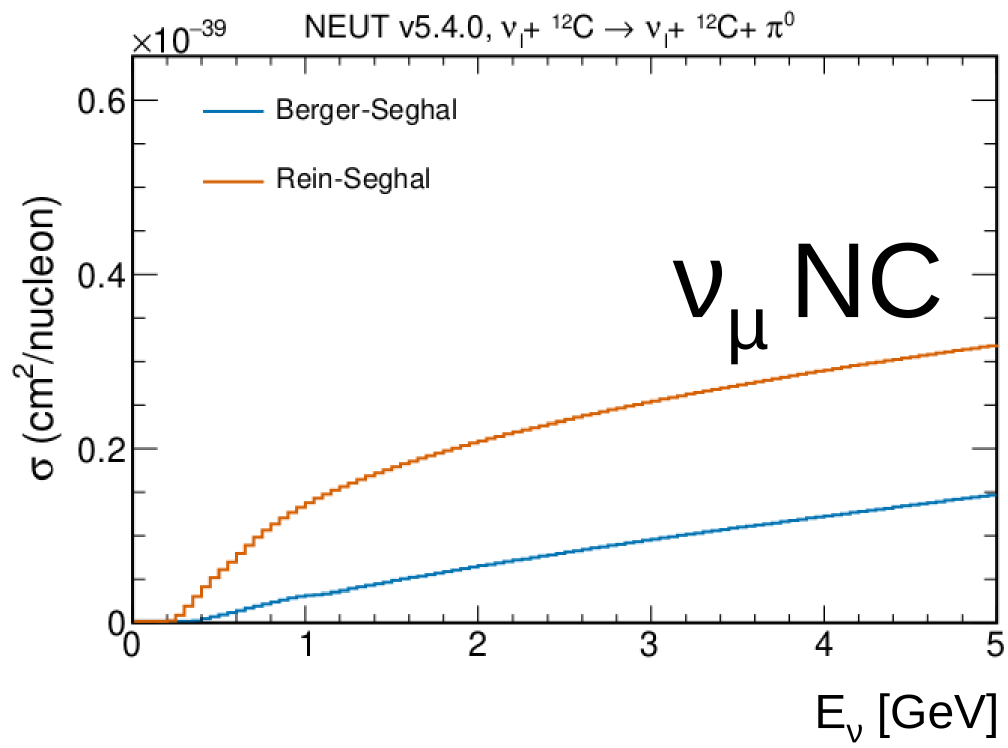
- Pion Final State Interactions in NEUT

- A few items I think need work:
  - transition from resonant to DIS regions
  - hadronic system in multi-pion mode

Coherent pion production

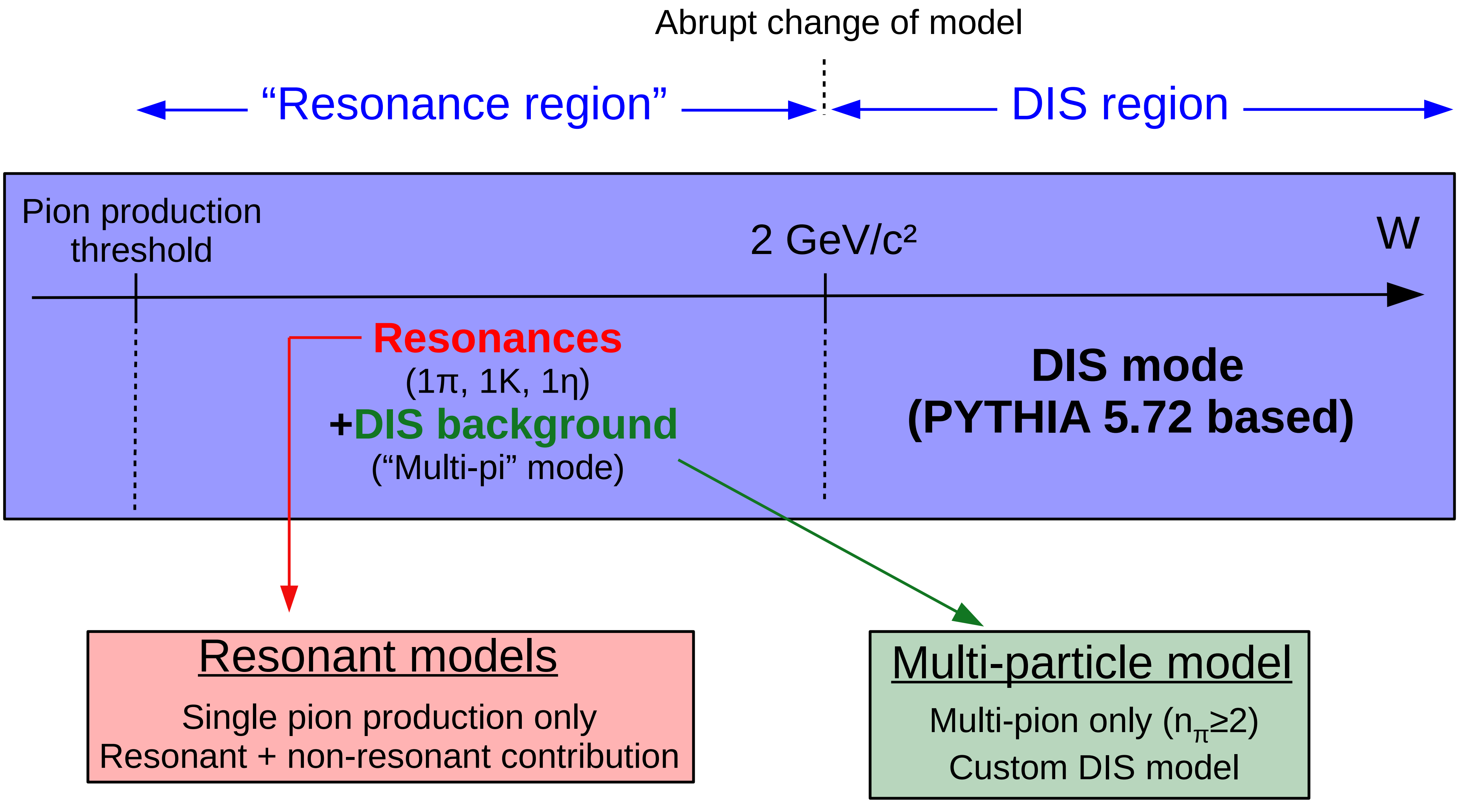
- 3 models implemented:
  - Rein-Sehgal (Nucl. Phys. B 223, 29 (1983))
  - Kartavtsev-Paschos (Phys. Rev 74, 054007 (2006))
  - Berger-Sehgal (Phys. Rev. D 79, 053003 (2009))
- Changed default model from RS to BS from NEUT 5.4.0





(Plots by S. Cao, KEK)

Pion production in the resonance region



No 2π/3π resonances

No DIS contribution to single pion production below W<2 GeV

Resonant pion production
Current implementation

- Based on Rein-Sehgal model (Ann. of Phys. 133(1981), Z.Phys.C 35(1987))
- Lepton mass corrections (Phys. Rev. D76, 113004 (2007))
- Includes non-resonant background from RS prescription

As is standard in NEUT, 2 different steps:
- ➔ Pre-calculate cross-section for this mode
- ➔ Actual generation of the events (kinematics)

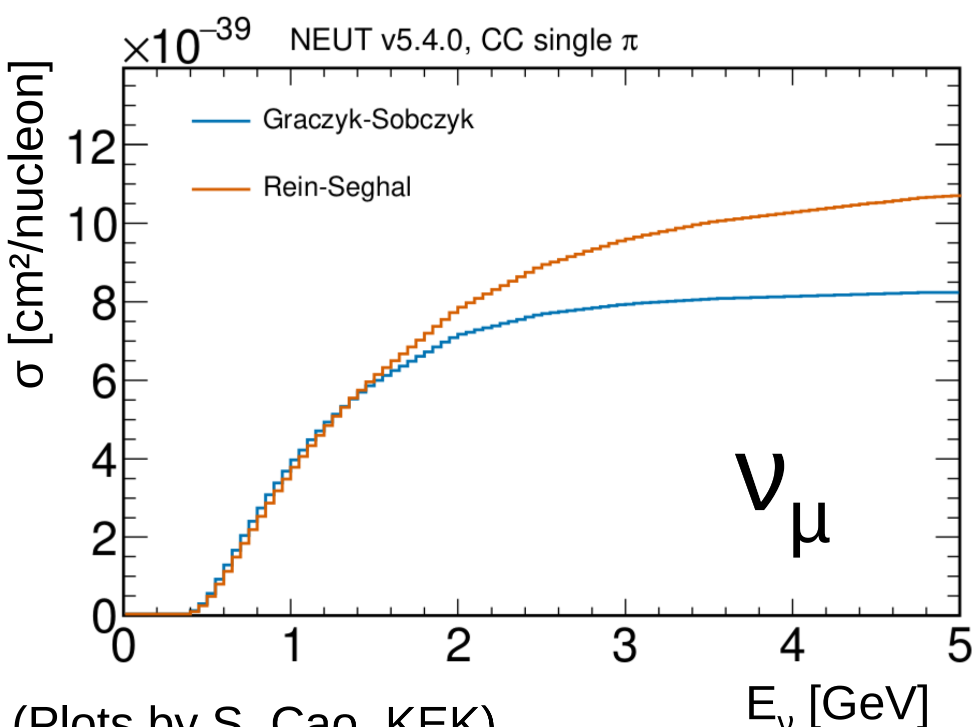
- Cross-section = resonance amplitude x probability to decay into π+baryon
- 18 resonances considered (up to 2 GeV/c^2)
  (width, masses, branching ratios, … not updated recently)
- Integrated over allowed kinematic region in (W,q^2)

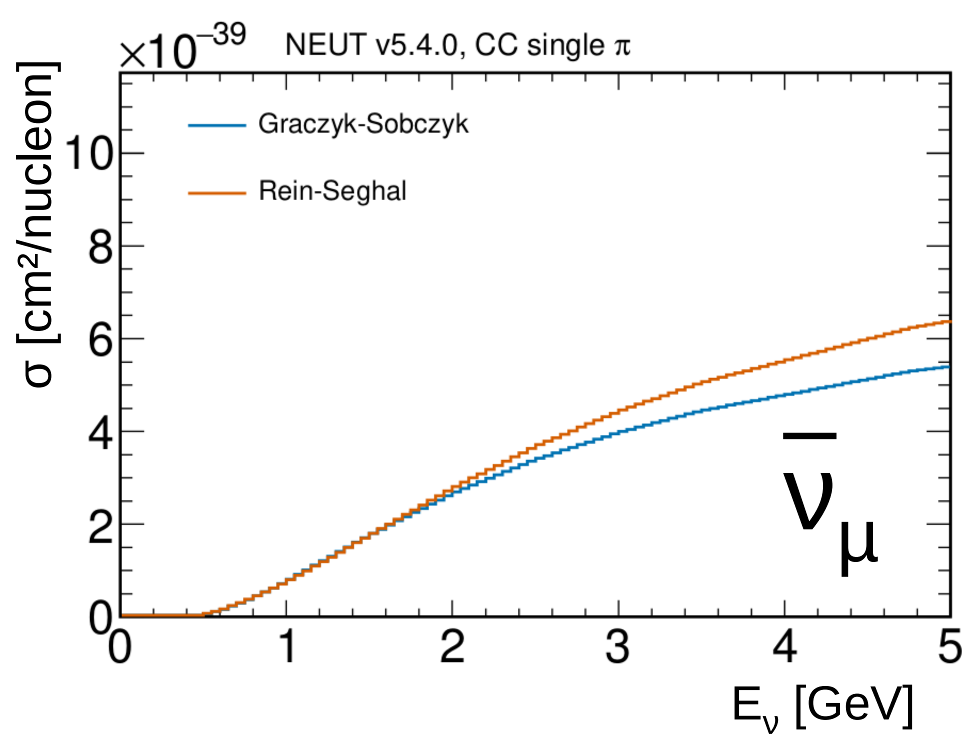
Resonant pion production
Current implementation

Can use two different sets of form factors:

- Standard RS with M_A=1.21 GeV/c² (or 1.11 GeV/c²)
- Graczyk-Sobczyk

Default is GS with values tuned from a fit of ANL and BNL data (P.Rodrigues et al.):
M_A= 0.95 GeV/c², C_A^5=1.01, $I_{1/2}$=1.3

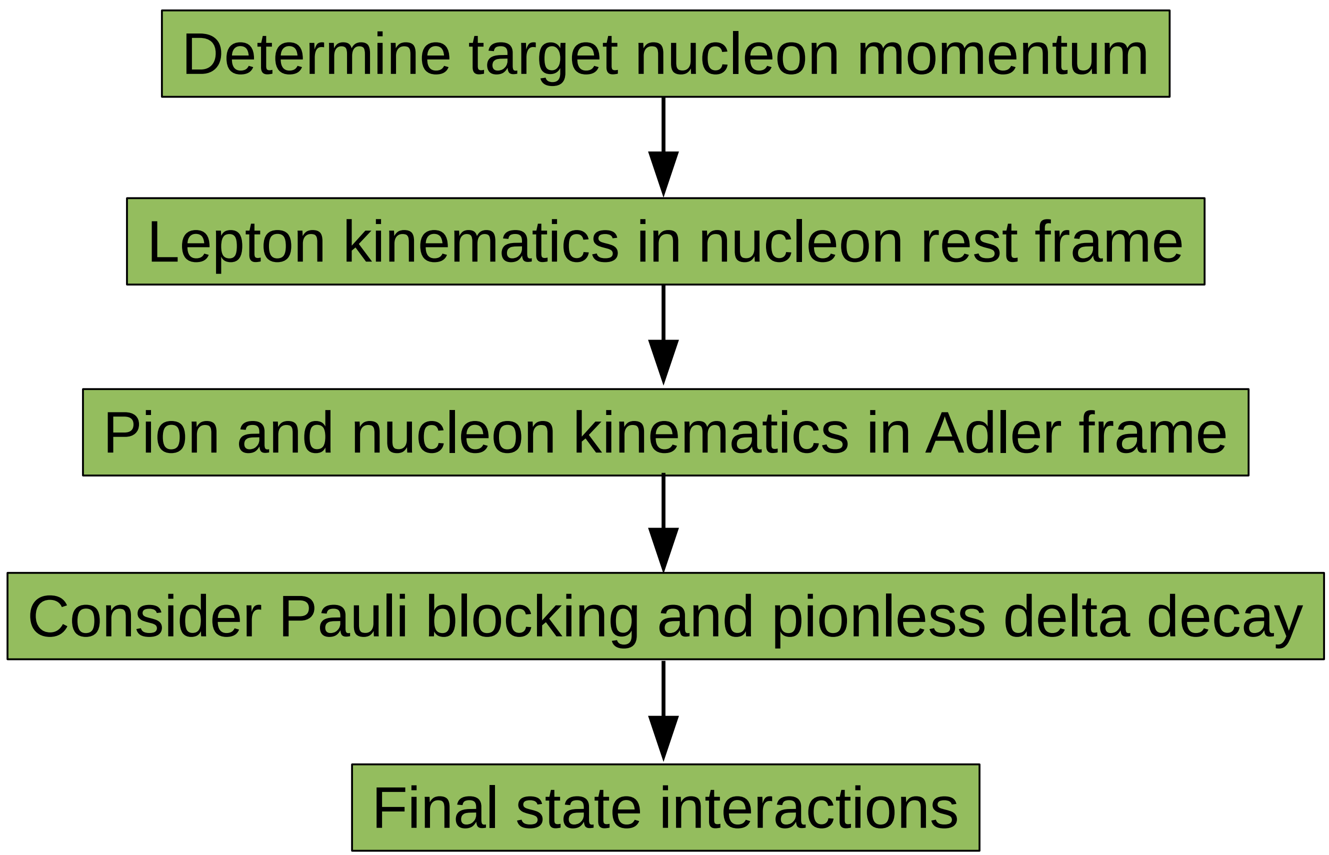




(Plots by S. Cao, KEK)

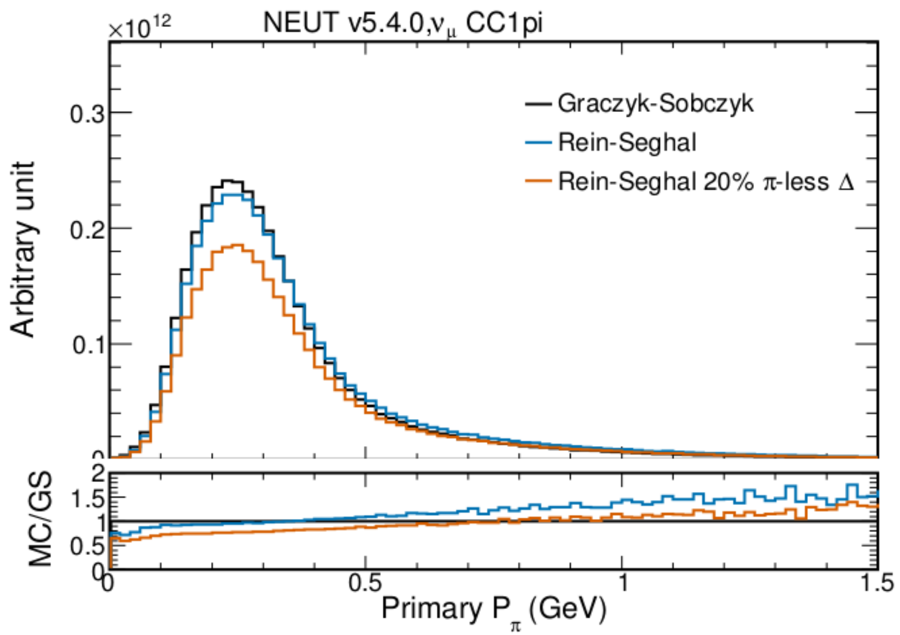
Resonant pion production
Event generation

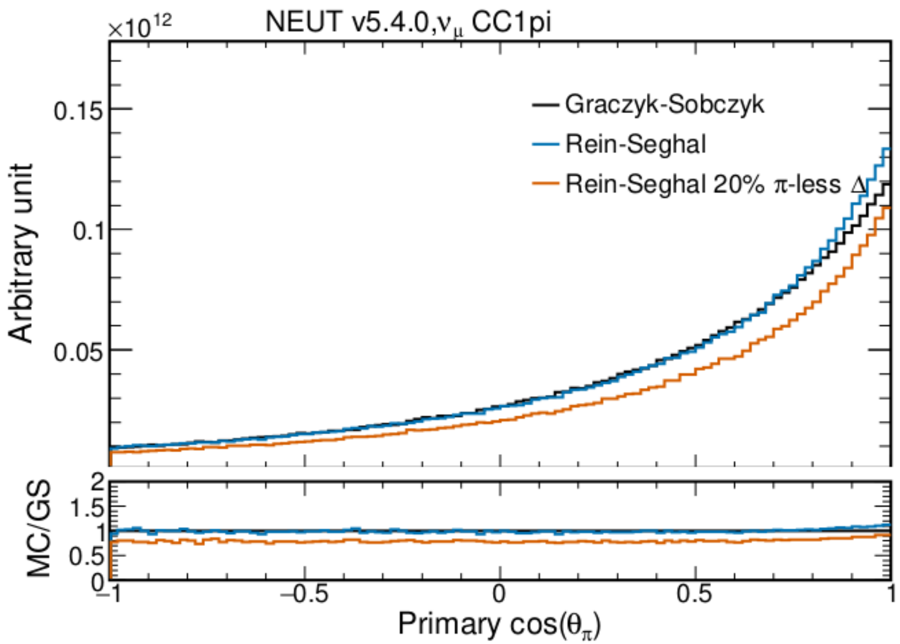
- Simple nuclear effects: RFG without binding energy and same Fermi momentum as for a CCQE model. No modification of Δ width.
- Pauli blocking implemented for nucleon from delta decay: 2-3% of interactions blocked
- (20% pionless delta decay if 2p2h interactions not enabled)



Resonant pion production
Pion direction

- Use RS method for P_{33} (1232)
- Isotropic in Adler's frame for other resonances
- Work by C. Wret to use RS method for the 4 dominant resonances in the future





Pion kinematics for CC single pion modes, ν_μ with T2K off-axis flux, by S. Cao

Resonant pion production
Plans for the future

Plan to include new model for single pion production in the future:
- MK model
- DCC model

- First version of MK model implemented in NEUT (C. Wret)
  - From NEUT 5.4.1 (not released)
  - based on Phys. Rev. D 97, 013002 (2018)
- Waiting for additional work by Minoo to be complete to use it as default model

- Implementation of DCC model just started

Multi-pion model
Overview

- Multi-pion mode describes the multiparticle ($n_{had} \geq 3$) component in the region 1.3 GeV/c² < W < 2GeV/c²

- Deep-inelastic model with the component $n_{had}=2$ removed

- In this region PYTHIA cannot be used: custom model

- Assumes that all the events have:
  - one outgoing lepton
  - one outgoing baryon
  - n outgoing pions (n>1)

- No Kaons, η: assume only resonant production for those particles for W<2 GeV/c²

- Many changes to this mode between NEUT 5.3.4 and 5.3.6: bug fixes + model updates (list in backup)

Multi-pion model
Cross-section calculation

- Cross-section for this mode is the standard DIS cross-section, reduced to take into account the fact that we only keep events with $n_{had} \geq 3$
- Calculated by integrating $d^2\sigma/dxdy$ over possible values of x and y
  - Bjorken x ≈ fraction of the nucleon momentum carried by the struck quark
  - Bjorken y: fraction of the neutrino energy transferred to the hadronic system

$d^2\sigma/dxdy$ parametrized in terms of structure functions $F_1, \ldots, F_5$

$$\frac{d^2\sigma}{dxdy} \propto \sum_{i=1}^{5} \alpha_i \times F_i(x, Q^2)$$

- Use modified Calland-Gross and Albright-Jarlskog relations to relate F_1, F_4, F_5 to F_2 and xF_3

$$F_1(x,Q^2) = \frac{1}{2x} F_2(x,Q^2) \times \left(\frac{1+4M^2x^2/Q^2}{1+R(x,Q^2)} \right)$$

$$F_4(x,Q^2) = 0$$

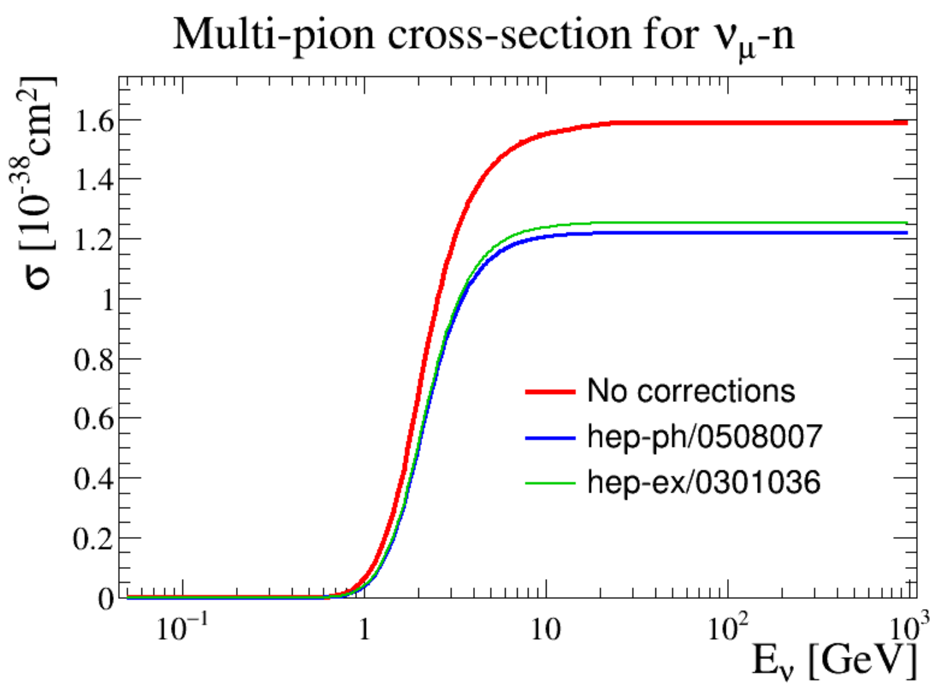
$$F_5(x,Q^2) = \frac{F_2(x,Q^2)}{x}$$

- Finally use quark-parton model to compute F_2 and xF_3 from Parton Distribution Functions

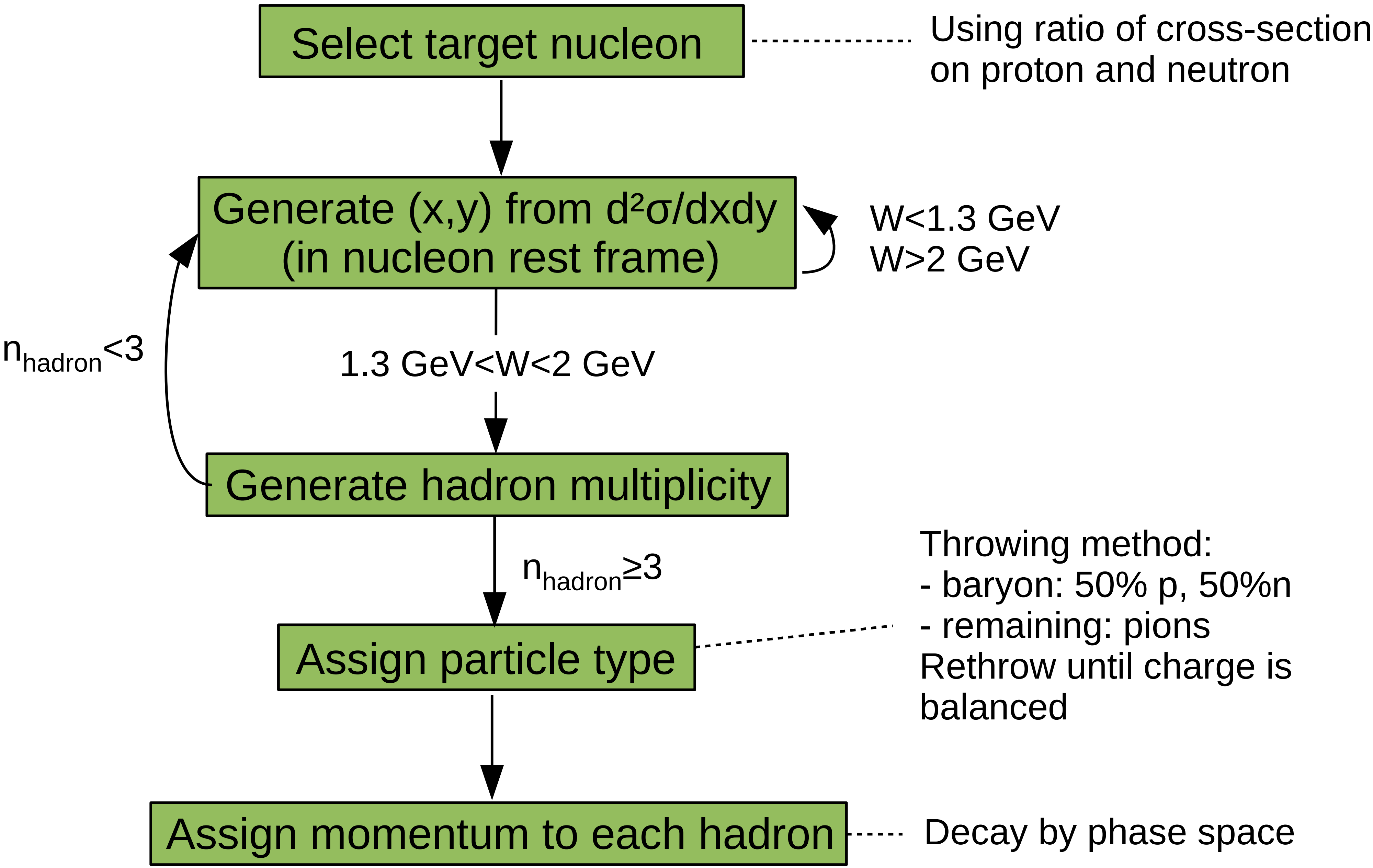
Multi-pion model
Bodek-Yang model

- For PDFs, using Bodek-Yang model: GRV98 LO PDFs modified to allow to go to low Q^2
- Model with free parameters, determined by a fit of electron scattering and photo-production data
- Many different version, latest ones not implemented in generators
- Values of the parameters can change significantly between versions, but still give similar predictions

Parameter	hep-ex/0301036 NEUT < 5.3.6	hep-ph/0508007 NEUT ≥ 5.3.6
A	0.419	0.538
B	0.223	0.305
C_{val1}^{d}	0.544	0.202
C_{val1}^{u}	0.544	0.291
C_{val2}^{d}	0.431	0.255
C_{val2}^{u}	0.413	0.189
C_{sea}^{d}	0.380	0.621
C_{sea}^{u}	0.380	0.363

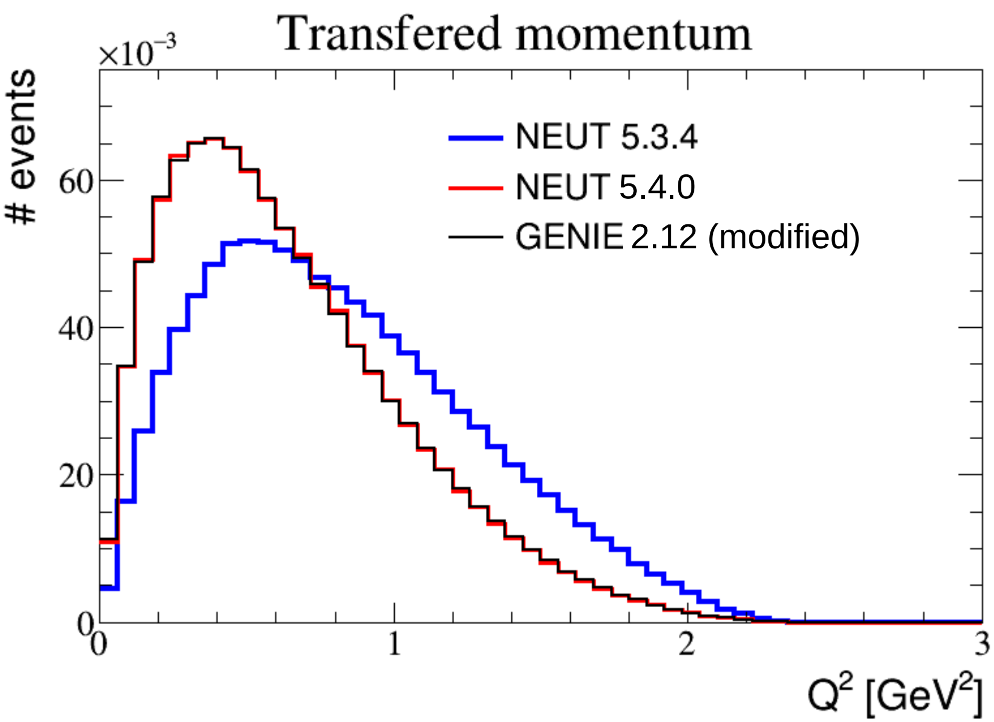


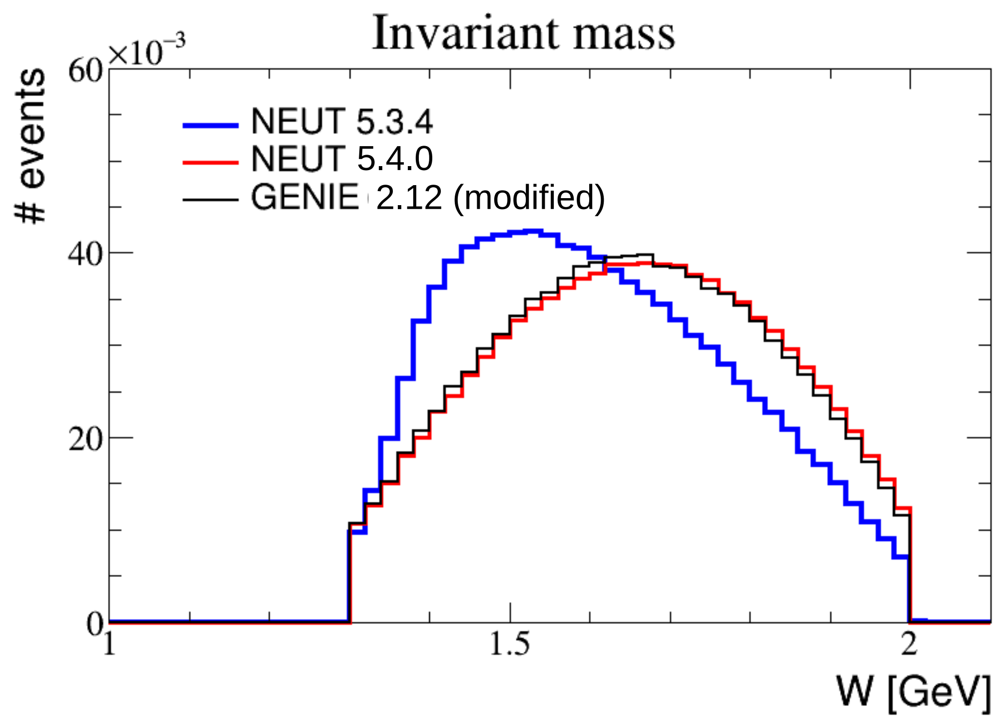
Multi-pion model Flow



Multi-pion model
Comparison to GENIE AGKY model

- This mode uses similar method and inputs to generate (x,y)/(W,Q^2) to the GENIE low W (AGKY) model
- Prediction of the 2 generators for (W,Q^2) agree after the updates from NEUT 5.3.4 to 5.4.0





Note: Need special settings and cuts for generators to match. See talk at Nustec SIS/DIS workshop for details

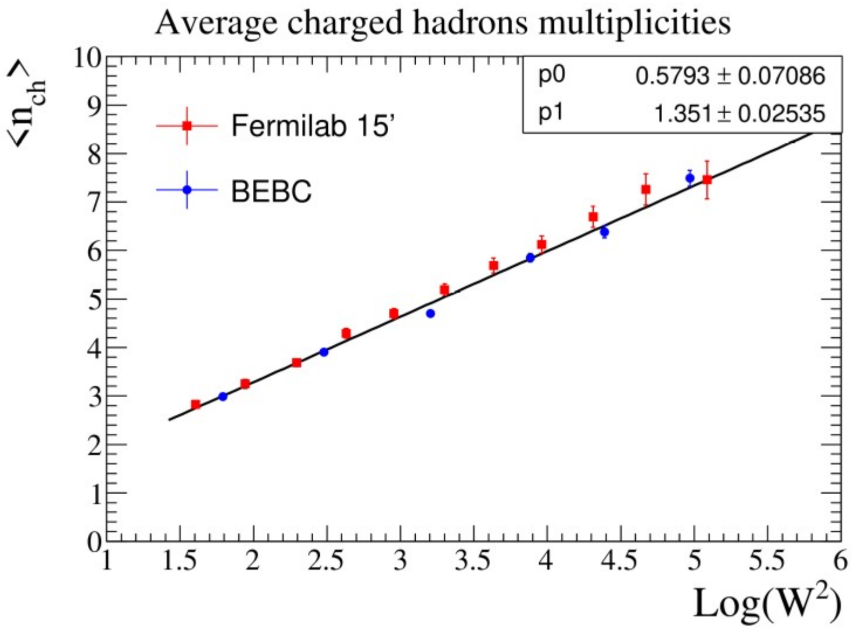
2 GeV neutrinos on free protons
Normalized by area

Multi-pion model
Multiplicity model

- To determine the number of hadrons produced, use a multiplicity model
- Gives the probability to produce a given number of hadrons as a function of W, $\nu/\bar{\nu}$ and target nucleon
- Based on KNO scaling, with free parameters obtained from fits of bubble chamber data

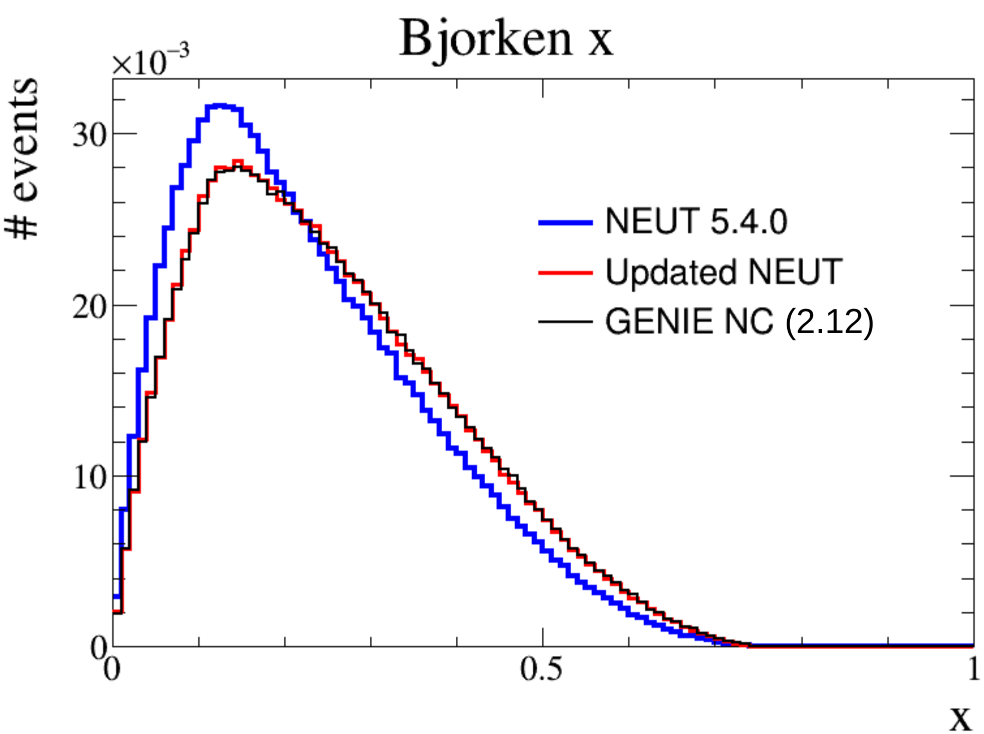
In NEUT 5.4.0, three hadron multiplicity models for the multi-pi mode

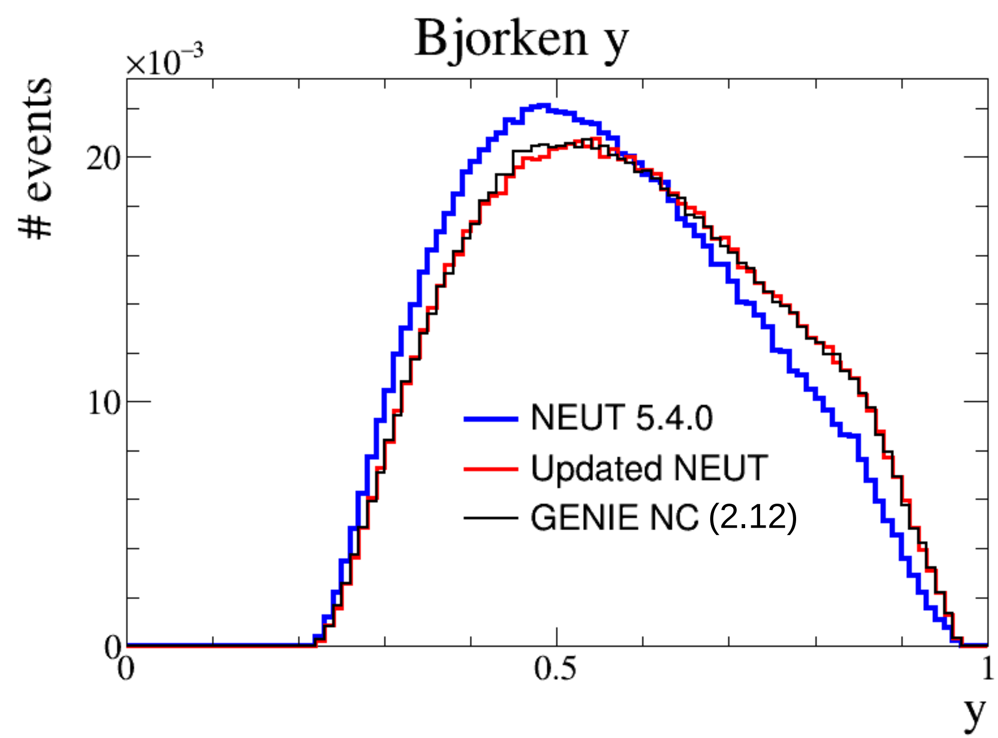
- NE-MULT=0: NEUT default (model used up to now, with a few minor changes)
- NE-MULT=1: from deuterium bubble chamber fits (CB, hep-ph:1607.06558)
- NE-MULT=2: AGKY model (GENIE model, hep-ph:0904.4043)



Multi-pion model
Neutral current modes

- In 5.4.0, NC multi-pion mode uses CC structure functions (without CKM matrix element), and NC DIS cross-section obtained from CC one
- Initial work on implementing correct NC structure functions.
  With this change, low W NC mode compatible with GENIE
  (2 GeV $\bar{\nu}_\mu$ on free neutrons, usual settings to have agreement)
- Next step will be to compute NC cross-section by integrating $d^2\sigma/dxdy$





<u>Note:</u> here also need special settings and cuts for generators to match.

DIS region

- Pure DIS mode for W>2 GeV/c² based on PYTHIA 5.72
- Cross-section calculated by integrating $d^2\sigma/dxdy$ (as for multi-pion mode)
- PYTHIA used for the actual event generation:
  - input E_ν and nucleon four-momentum (from simple RFG model)
  - Loop over PYTHIA event generation until W>2 GeV and right NC/CC type

Modified parameters in PYTHIA 5.72

```
*     Lower edge of allowed sqrt{s} [GeV]
      CKIN(1)     = 0.001
*     Lower cut-off on p_t [GeV/c]
      CKIN(5)     = 0.0001
*     Lower CM energy [GeV]
      PARP(2)     = 0.001
*     Switch to be allowed to decay or not
      MDCY(LUCOMP(111),1) = 0
      MDCY(LUCOMP(221),1) = 0
      MDCY(LUCOMP(311),1) = 0
      MDCY(LUCOMP(223),1) = 0
      MDCY(LUCOMP(130),1) = 0
      MDCY(LUCOMP(310),1) = 0
      MDCY(LUCOMP(331),1) = 1
**** without tau decay(decay at tauola)
      IF(ITAUFLGCORE.eq.1) THEN
        MDCY(LUCOMP(15),1) = 0
      ENDIF
```

Don't do decays of π^0, η, K^0, ω and τ
Decay η'

Pion Final State Interactions Overview

- Semi-classical cascade model:
  - pions propagated by steps through the nucleus
  - compute probability to interact at each step from mean free path
- 2 models used depending on pion momentum:
  - "Δ dominated" region p_π<500 MeV/c
  - high energy region p_π>500 MeV/c
- Linear transition between the 2 models in the region 400 MeV/c < p_π< 500 MeV/c

Interaction probability at each step depend on nuclear density

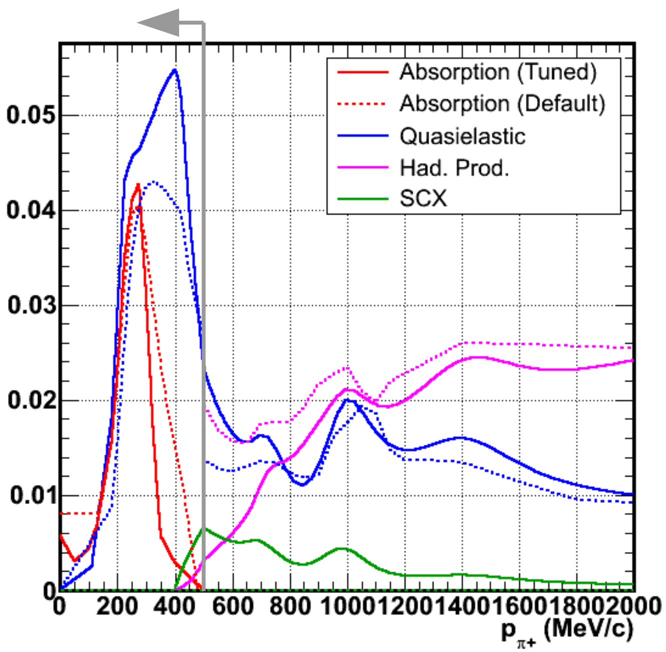
$$\frac{\rho(r)}{\rho_0} = \frac{1 + w\frac{r^2}{c^2}}{1 + \exp\left(\frac{r-c}{\alpha}\right)}$$

- w=0 for ^{16}O
- extracted from electron scattering data for others (Jager et al., 1974)
- α,c also from electron scattering

Pion Final State Interactions Model for p_π<500 MeV

- Interaction probability from L.L.Salcedo et al. Nucl. Phys. A484(1998) 79 (valid for 85 MeV<T_π<350 MeV extended to 0<p_π<500 MeV)
- Absorption probability from E.Oset et al. Nucl. Phys. A468 (1987) 631
- Neglect elastic scattering

Tuning of mean free path
- using π^+-^{12}C data
- Iterative tuning “by hand”

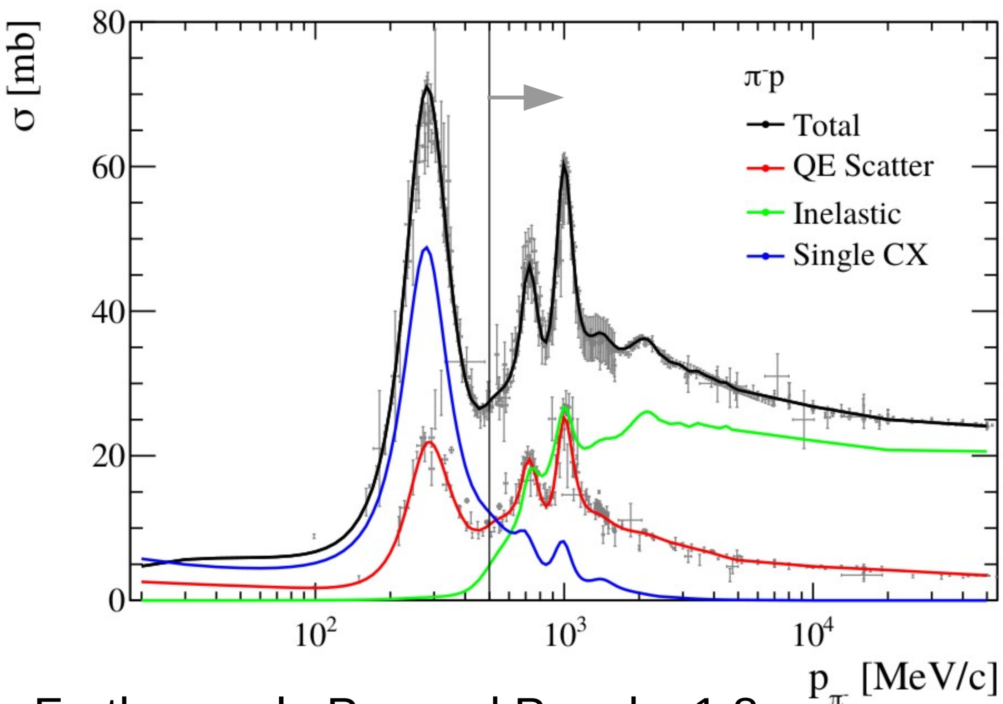


Kinematics (QE):
- Use the results of phase shift analysis of π-N scattering (Rowe et al., PRC 18(1):584, 1978)
- Medium correction (from R.Seki et al., PRC27 (1983)) is applied to each phase shift
- Single charge exchange included assuming “Δ dominance”

Pion Final State Interactions Model for p_π>500 MeV

- Higher energy pions: assume nucleons ~ free nucleons in nucleus
- Get interaction probablility from $\pi^\pm$-p data assuming isospin symmetry
  - π^+-p ↔ π^--n
  - π^--p ↔ π^+-n, π^0-n
- Multiplicity for multi-pion production parameterized from bubble chamber data (J.Whitmore Phys. Rep. 27C (1976) 187)

Use SAID PWA fit of $\pi^\pm$-p data



Further scale P_{QE} and P_{SCX} by 1.8 from π^+-^{12}C and SCX data

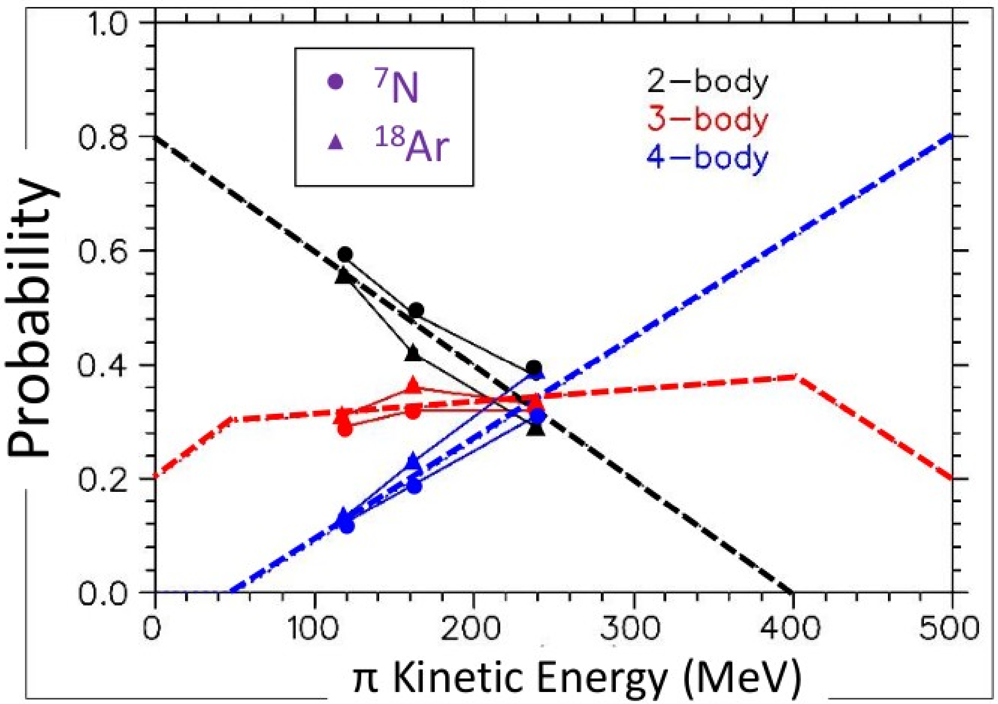
Kinematics

- Multi-pion: by phase space
- Single pion:
  - Simple elastic-like forward scatter for Tπ≥ 2 GeV
  - Phase shift from SAID PWA for Tπ<400 MeV
  - Transition between the 2 with quadratic probability between 400 MeV and 2 GeV

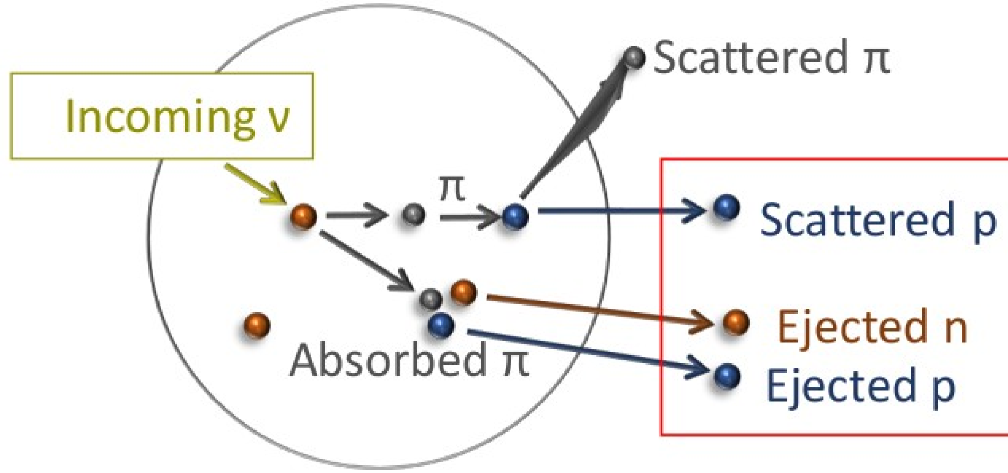
Pion Final State Interactions
Nucleon emission after pion absorption

By R. Tacik and P. de Perio

Nucleon multiplicity
from π-A absorbtion data
(LADS collaboration, Rowntree et al, PRC, 60:054610, 1999)



Dashed line is model used in NEUT



Nucleon type:
- From Rowntree et al. for π^+
- Use isospin symmetry for π^-
- Simple model for π^0

Nucleon kinematics:
- 2-body: follow kinematics of $\pi^+ d \rightarrow pp$, based on B. G. Ritchie PRC 44:533 (1991)
- others: by phase space

Pion Final State Interactions
New tuning of interaction strength

E. S. Pinzon Guerra et al., Phys. Rev. D 99, 052007 (2019)
Used in NEUT from 5.4.0

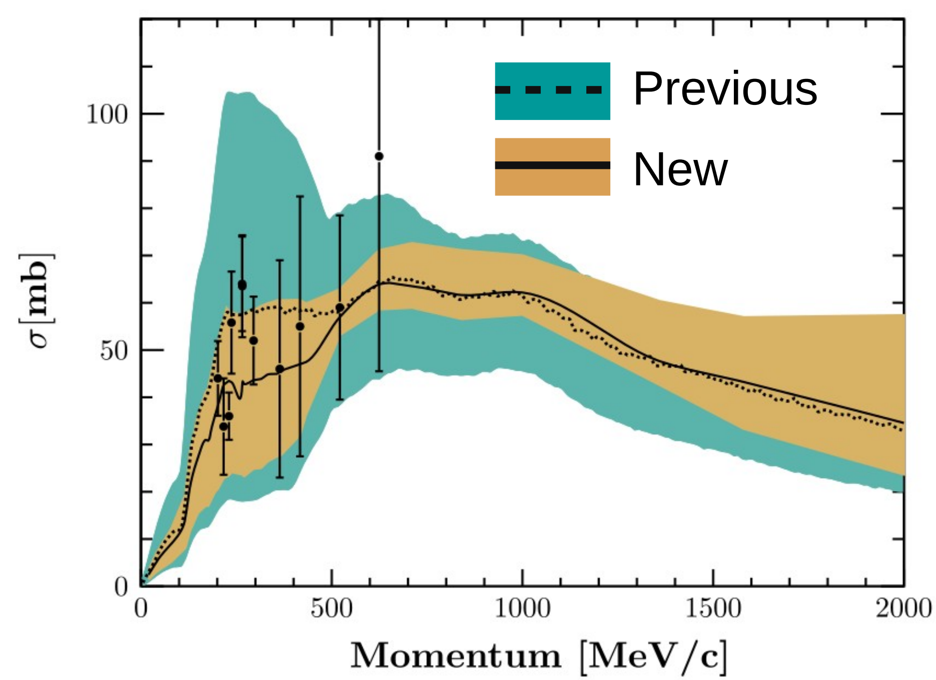
Tune strength of 4 interaction channels:
- low momentum QE and absorbtion
- High momentum QE and multi-pion production

+ fraction of charge exchange for low momentum QE

Data on C, O, Al, Fe, Cu, Pb
π± beams between 60 MeV and 2 GeV

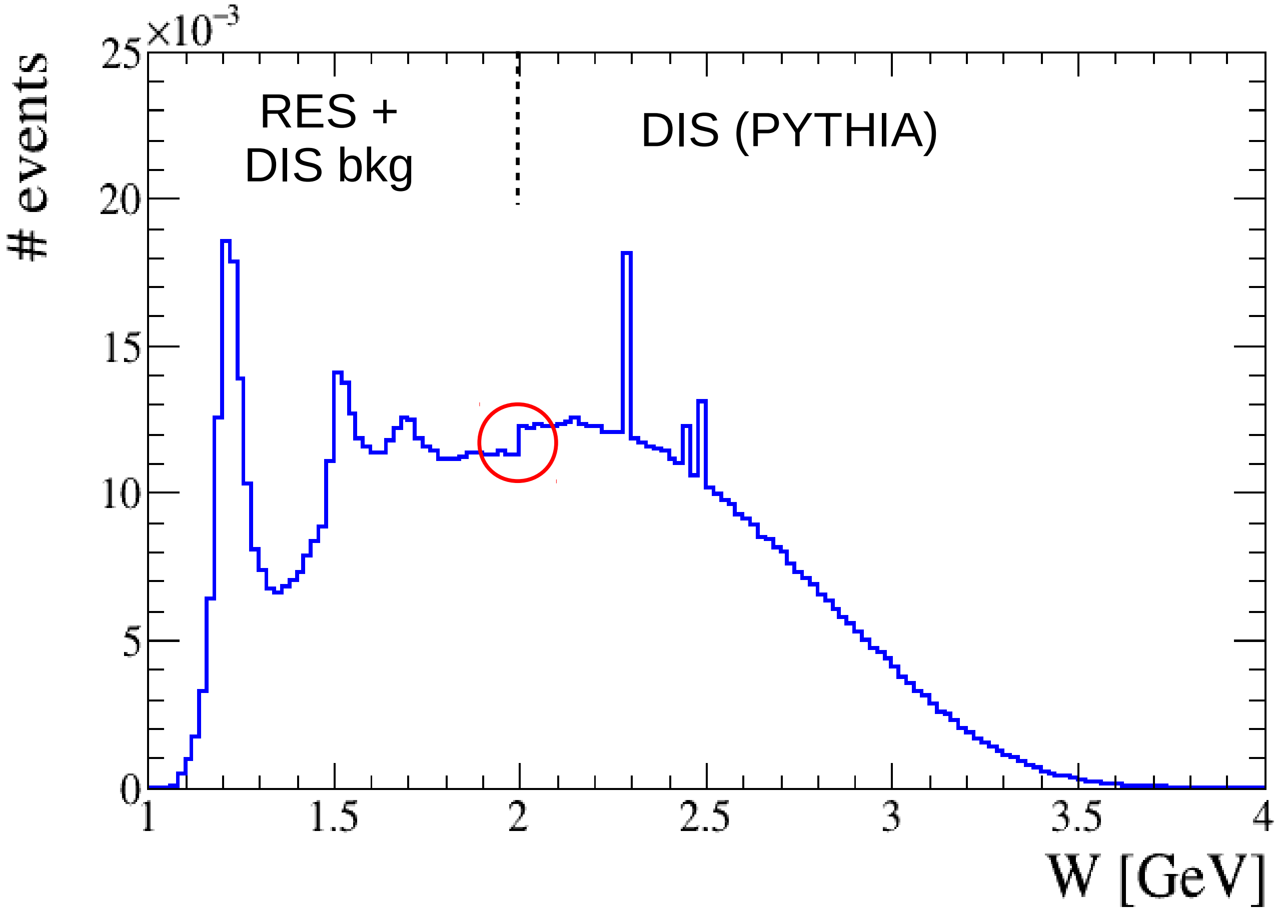
Parameter	Best fit ± 1σ Carbon-only	Light nuclei	All nuclei
FEFQE	1.07 ± 0.07	1.08 ± 0.07	1.08 ± 0.07
FEFABS	1.24 ± 0.05	1.25 ± 0.05	1.26 ± 0.05
FEFCX	0.79 ± 0.05	0.80 ± 0.04	0.80 ± 0.04
FEFINEL	0.63 ± 0.27	0.71 ± 0.21	0.70 ± 0.20
FEFQEH	2.16 ± 0.34	2.14 ± 0.24	2.13 ± 0.22
$\chi^2(N_{dof})$	18.36(23)	40.14(40)	53.48(55)

CX for π^+-^{12}C



Transition between RES and DIS regions

See a clear discontinuity when changing models from resonant + bkg to pure DIS at W=2 GeV



6 GeV ν_μ on Fe target

Transition between RES and DIS regions

Discontinuity at $W=2$ GeV/c^2 hints at a problem, but could be many reasons

- (duality not working for ν-A)?
- Problem with resonance model?
- Problem with multi-pion normalization?
- Problem with W shape for multi-pion?
- Problem with W shape from PYTHIA?

- Pure DIS for $W \geq 2$ GeV
- Scheme based on the number of hadrons below:
  - $n_{had}=2$: use resonant model
  - $n_{had} \geq 3$: use DIS "multi-pion" model

As a result, multiplicity model matters a lot for multi-pion mode:

- correction factor on the cross-section → normalization of the multi-pion component
- W dependance of $P(n_{had} \geq 3)$ → W shape of the multi-pion component

Multi-pion mode
Uncertainty on multiplicity model

- Use data from bubble chamber experiments to measure free parameters
- To decorrelate from final state interaction modelisation, use data from hydrogen and deuterium experiments

Author(s), experiment, publ. date	Ref.	Target	W^2 range	Kinematic cuts	Intercept a	Slope b
			$\nu_\mu p \to \mu^- X^{++}$			
Coffin *et al.*, FNAL E45, 1975	[21]	H	4–200		1.0 ± 0.3	1.1 ± 0.1
Chapman *et al.*, FNAL E45, 1976	[22]	H	4–200		1.09 ± 0.38	1.09 ± 0.03
Bell *et al.*, FNAL E45, 1979	[23]	H	4–100	$Q^2 = 2 - 64\ \mathrm{GeV}^2$		1.35 ± 0.15
Kitagaki *et al.*, FNAL E545, 1980	[26]	^{2}H	1–100		0.80 ± 0.10	1.25 ± 0.04
Zieminska *et al.*, FNAL E545, 1983	[27]	^{2}H	4–225		0.50 ± 0.08	1.42 ± 0.03
Saarikko *et al.*, CERN WA21, 1979	[28]	H	3–200		0.68 ± 0.04	1.29 ± 0.02
Schmitz, CERN WA21, 1979	[29]	H	4–140		0.38 ± 0.07	1.38 ± 0.03
Allen *et al.*, CERN WA21, 1981	[30]	H	4–200		0.37 ± 0.02	1.33 ± 0.02
Grässler *et al.*, CERN WA21, 1983	[32]	H	11–121		-0.05 ± 0.11	1.43 ± 0.04
Jones *et al.*, CERN WA21, 1990	[33]	H	16–196		0.911 ± 0.224	1.131 ± 0.086
Jones *et al.*, CERN WA21, 1992	[34]	H	9–200		0.40 ± 0.13	1.25 ± 0.04
Allasia *et al.*, CERN WA25, 1980	[35]	^{2}H	2–60		1.07 ± 0.27	1.31 ± 0.11
Allasia *et al.*, CERN WA25, 1984	[38]	^{2}H	8–144	$Q^2 > 1\ \mathrm{GeV}^2$	0.13 ± 0.18	1.44 ± 0.06
			$\overline{\nu}_\mu p \to \mu^+ X^0$			
Derrick *et al.*, FNAL E31, 1976	[14]	H	4–100	$y > 0.1$	0.04 ± 0.37	1.27 ± 0.17
Singer, FNAL E31, 1977	[15]	H	4–100	$y > 0.1$	0.78 ± 0.15	1.03 ± 0.08
Derrick *et al.*, FNAL E31, 1978	[16]	H	1–50		0.06 ± 0.06	1.22 ± 0.03
Derrick *et al.*, FNAL E31, 1982	[20]	H	4–100	$0.1 < y < 0.8$	-0.44 ± 0.13	1.48 ± 0.06
Grässler *et al.*, CERN WA21, 1983	[32]	H	11–121		-0.56 ± 0.25	1.42 ± 0.08
Jones *et al.*, CERN WA21, 1990	[33]	H	16–144		0.222 ± 0.362	1.117 ± 0.141
Jones *et al.*, CERN WA21, 1992	[34]	H	9–200		-0.44 ± 0.20	1.30 ± 0.06
Allasia *et al.*, CERN WA25, 1980	[35]	^{2}H	7–50		0.55 ± 0.29	1.15 ± 0.10
Barlag *et al.*, CERN WA25, 1981	[36]	^{2}H	6–140		0.18 ± 0.20	1.23 ± 0.07
Barlag *et al.*, CERN WA25, 1982	[37]	^{2}H	6–140		0.02 ± 0.20	1.28 ± 0.08
Allasia *et al.*, CERN WA25, 1984	[38]	^{2}H	8–144	$Q^2 > 1\ \mathrm{GeV}^2$	-0.29 ± 0.16	1.37 ± 0.06
			$\nu_\mu n \to \mu^- X^+$			
Kitagaki *et al.*, FNAL E545, 1980	[26]	^{2}H	1–100		0.21 ± 0.10	1.21 ± 0.04
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Allasia *et al.*, CERN WA25, 1984	[38]	^{2}H	8–144	$Q^2 > 1\ \mathrm{GeV}^2$	1.75 ± 0.12	1.31 ± 0.04
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Barlag *et al.*, CERN WA25, 1982	[37]	^{2}H	2–140		0.80 ± 0.09	0.95 ± 0.04
Allasia *et al.*, CERN WA25, 1984	[38]	^{2}H	8–144	$Q^2 > 1\ \mathrm{GeV}^2$	0.22 ± 0.21	1.08 ± 0.06

Phys. Rev. C 88, 065501 (2013)

Many problems:
- inconsistent results between datasets
- actual data hard to find
- no systematic uncertainties most of the time

- NEUT model 0 uses [16] ($\overline{\nu}$-p) for all types
- GENIE uses [27] for ν and [37] for $\overline{\nu}$, and symmetry νp ↔ νn for some parameters

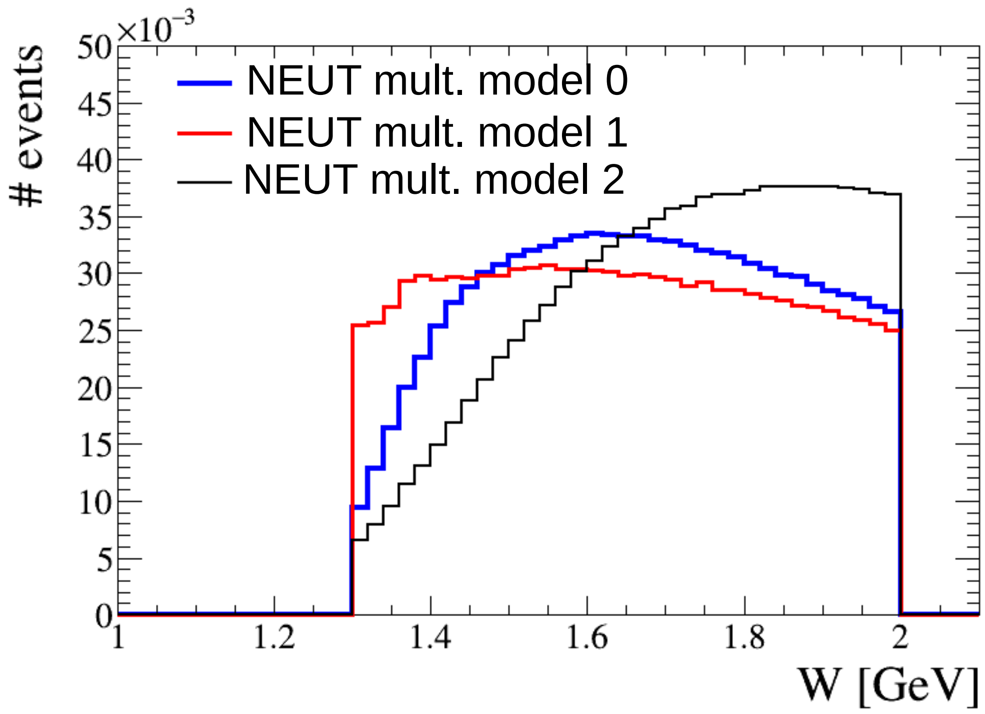
$$\langle n_{ch} \rangle = a + b \times \log(W^2)$$

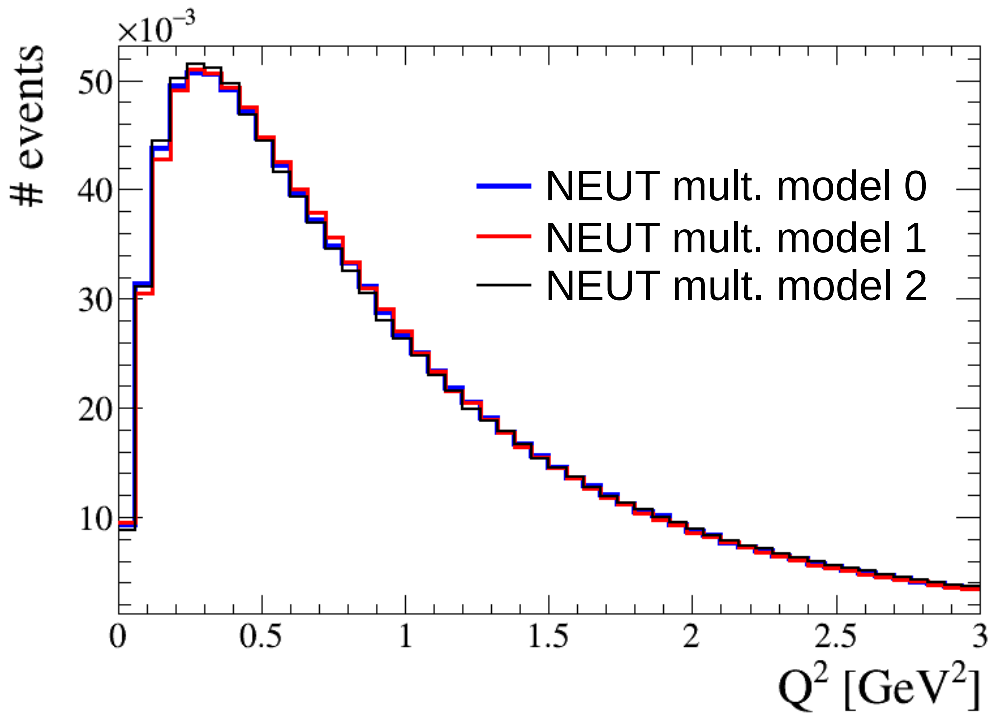
Multi-pion mode
Uncertainty on W distribution

- Generate (x,y) based on throwing method, keeping only events with $n_{had} \geq 3$
- In multiplicity models, multiplicity probability depends of W

$$\langle n_{ch} \rangle = a + b \times \log(W^2)$$

- Shape of W distribution of the multi-pion component is uncertain as a result of uncertainty on a and b



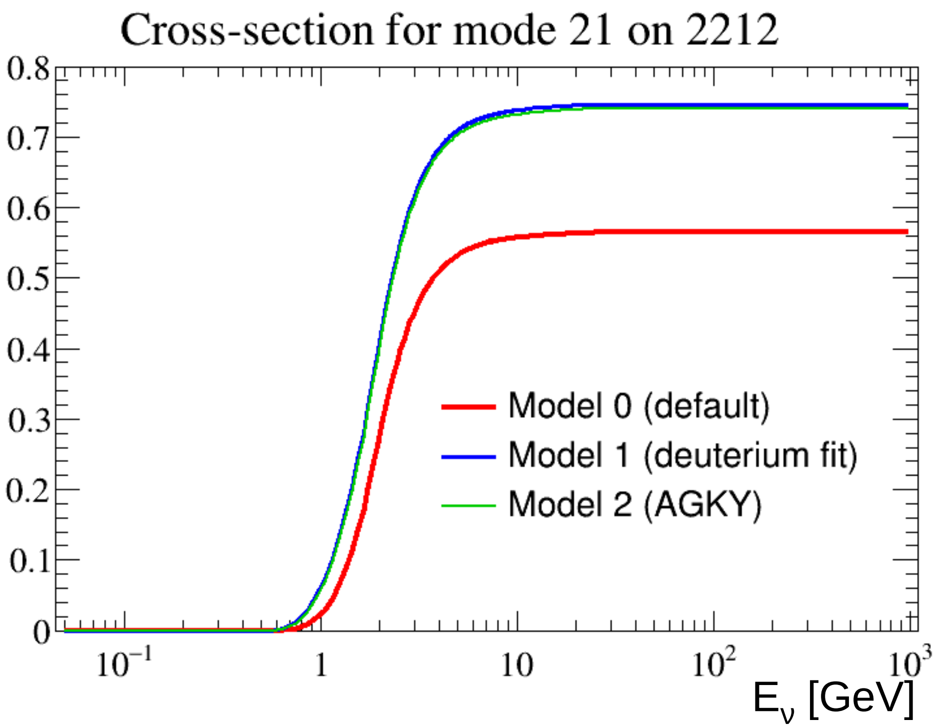


(T2K near detector flux, area normalized, low W mode W<2 GeV, $n_\pi \geq 2$)

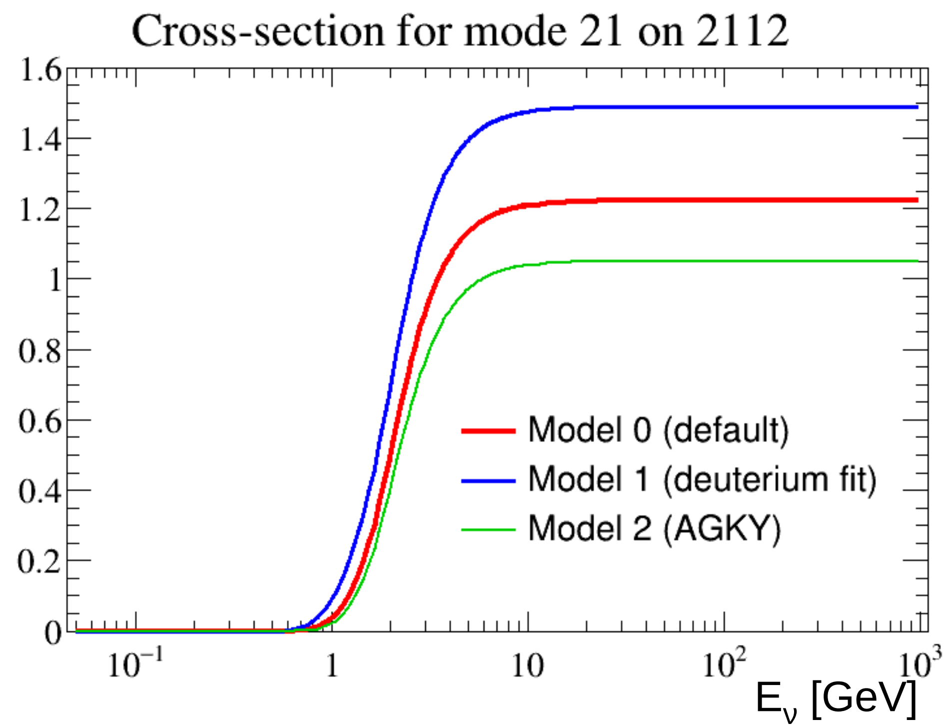
Non resonant background normalization
Uncertainty on multiplicity model

Multi-pi mode cross-section is obtained by multiplying the total DIS cross section for W<2 GeV by the fraction of events that have at least two pions

Neutrino on proton



Neutrino on neutron

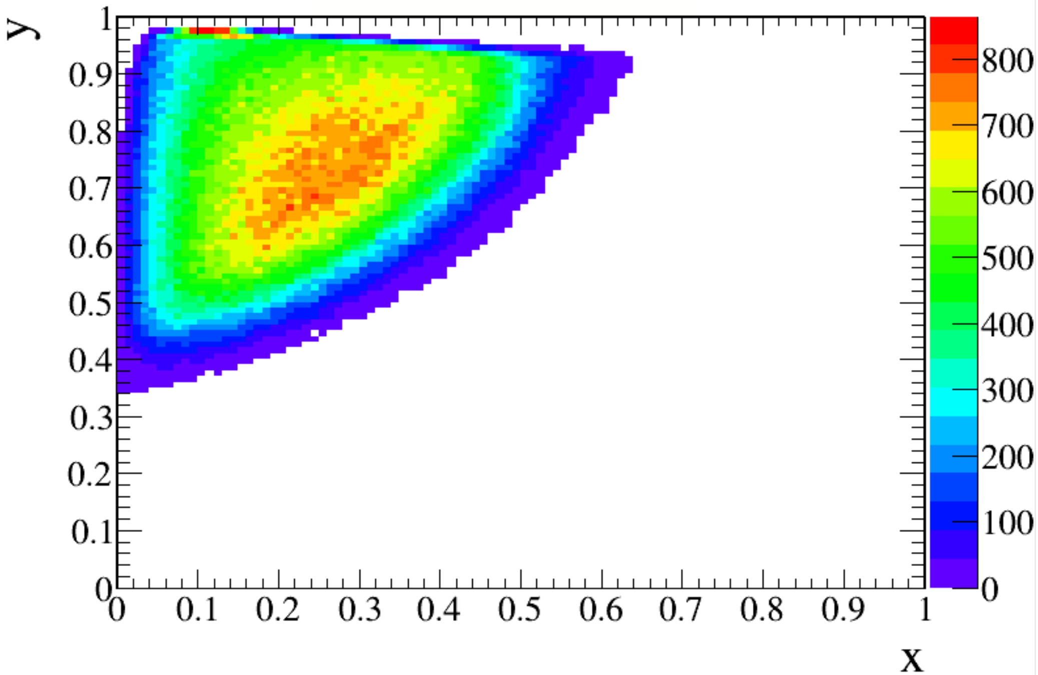


(In NEUT 5.4.0, cross-sections computed with model 0 are always used, regardless of the multiplicity model used)

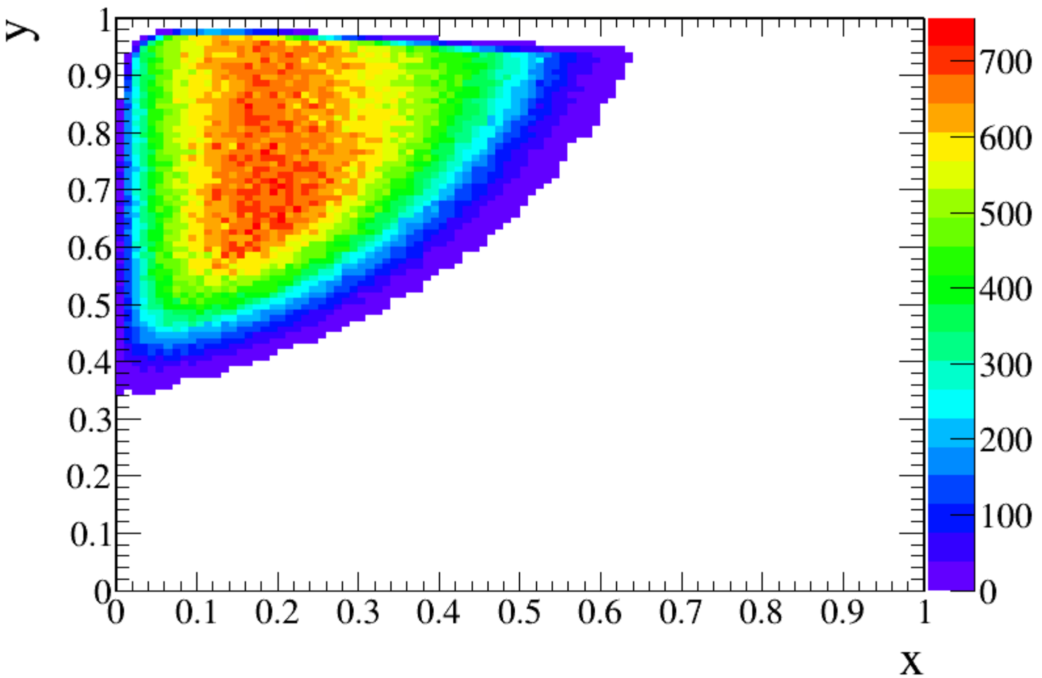
DIS (PYTHIA) mode
(x,y) generation

- Only provide neutrino and target nucleon four-momenta to PYTHIA
  Keep event if type (CC/NC) is the one desired, and W>2 GeV
  Redo PYTHIA generation with same inputs else
- As a result (x,y) distribution of events for PYTHIA events does not necessarily follow $d^2\sigma/dxdy$

From Pythia 5.72



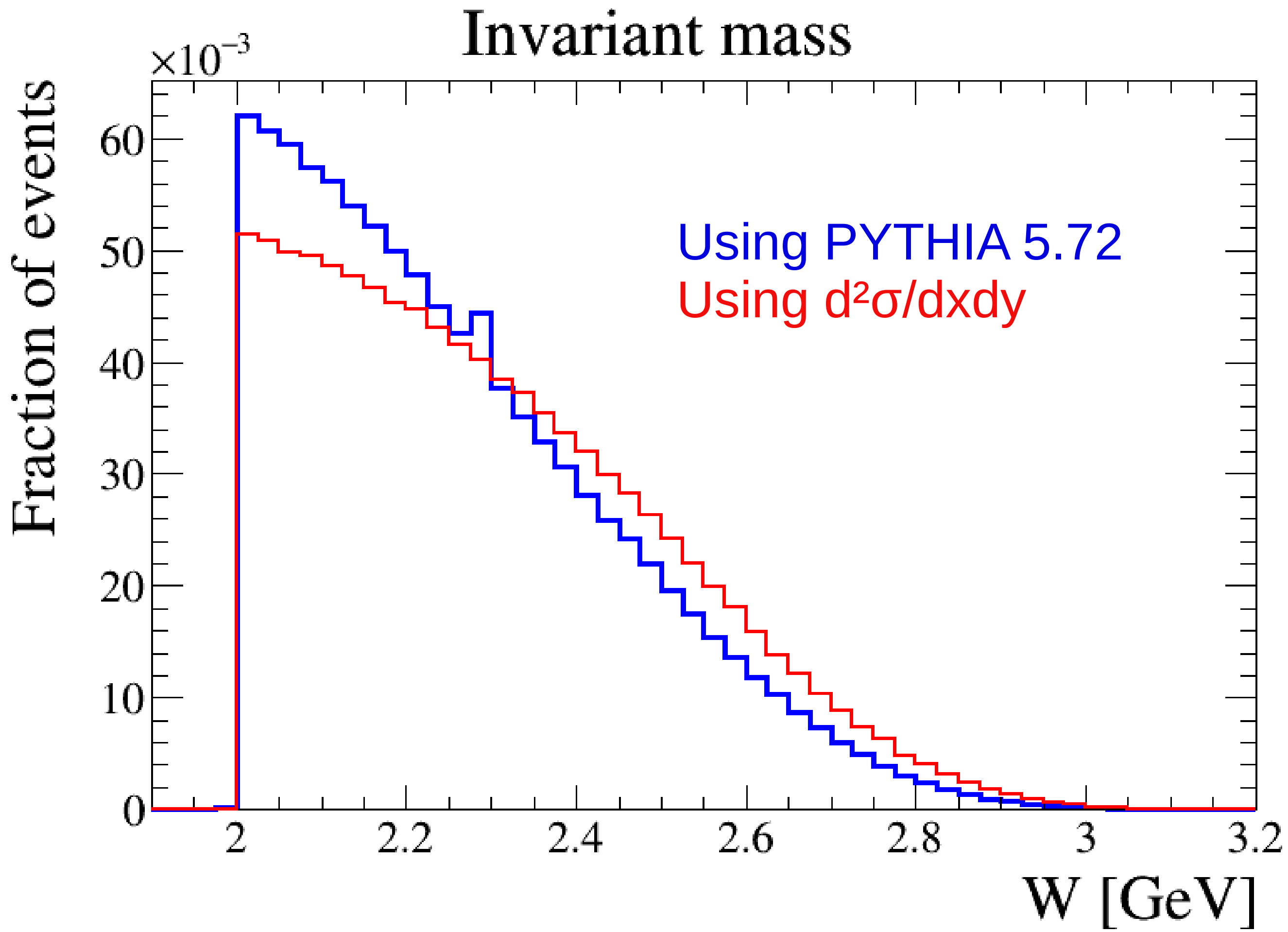
From $d^2\sigma/dxdy$ formula



4 GeV ν_μ on H_2O target

DIS (PYTHIA) mode
W distribution

As a result, W distribution obtained for this W>2 GeV mode differ from the distribution we expect from the standard $d^2\sigma/dxdy$ (used for multi-pion mode)



4 GeV ν_μ on H_2O target, normalized by area

DIS (PYTHIA) mode

At last year's NuSTEC workshop on SIS/DIS region, one of the PYTHIA author warned us about using PYTHIA at "low" W

"I would not trust PYTHIA for anything with less than 6 pions"

Physics assumptions/limitations:

Always want to confine previously deconfined color.

Target-m not really present in x-section or q/g kinematics.

Only tested for $W > 4$ GeV, small W in $e^+e^- \to h$ only, last global overview in 1987?

"Jet joining" not well-understood for low hadron multiplicity.

Strong isospin not traced in string.

Strings are traditionally non-interaction.

S. Prestel, "The LUND hadronization model"

⇨ Not clear the W distribution for the DIS/PYTHIA mode is reliable

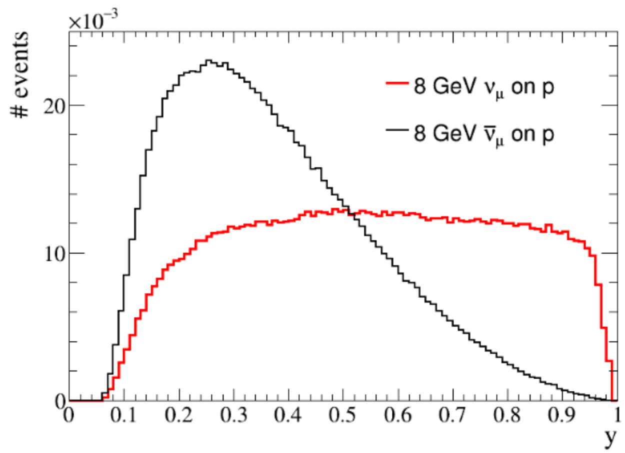
Importance of hadronic system

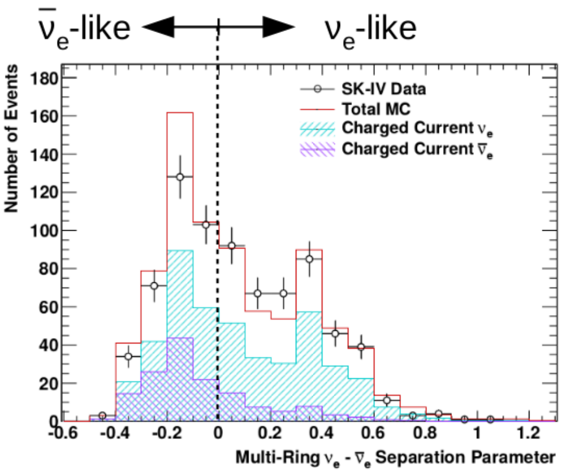
- NEUT is mainly used for Super-K (including T2K)
- In a water Cerenkov detector, different kind of pions look different (+ Cerenkov threshold for charged pions: appear as ring or Michel electrons depending on momentum)
- Topology of the event can change quite a bit depending on how the hadronic system is generated, can matter when trying to separate events with neural networks/deep learning

Statistical separation of ν_e and $\bar{\nu}_e$

8

Likelihood separation based on differences between DIS interactions of neutrinos and anti-neutrinos





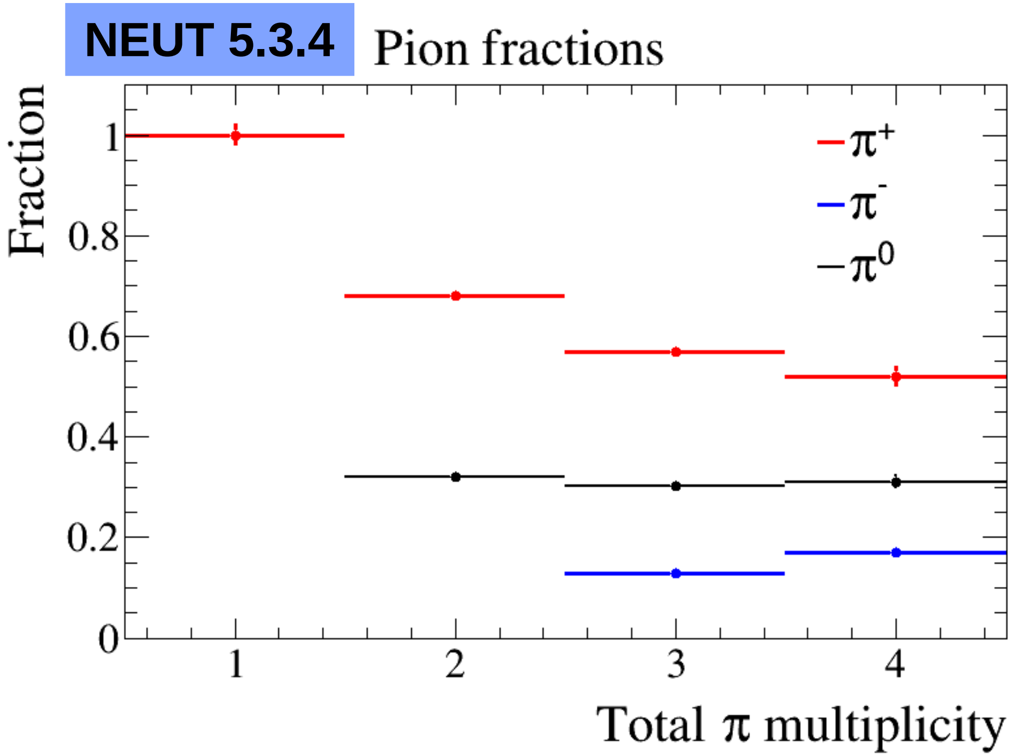
	Neutrino	Anti-neutrino
Nb of rings	More	Less
Nb of Michel e-	More	Less
Transverse momentum	Larger	smaller

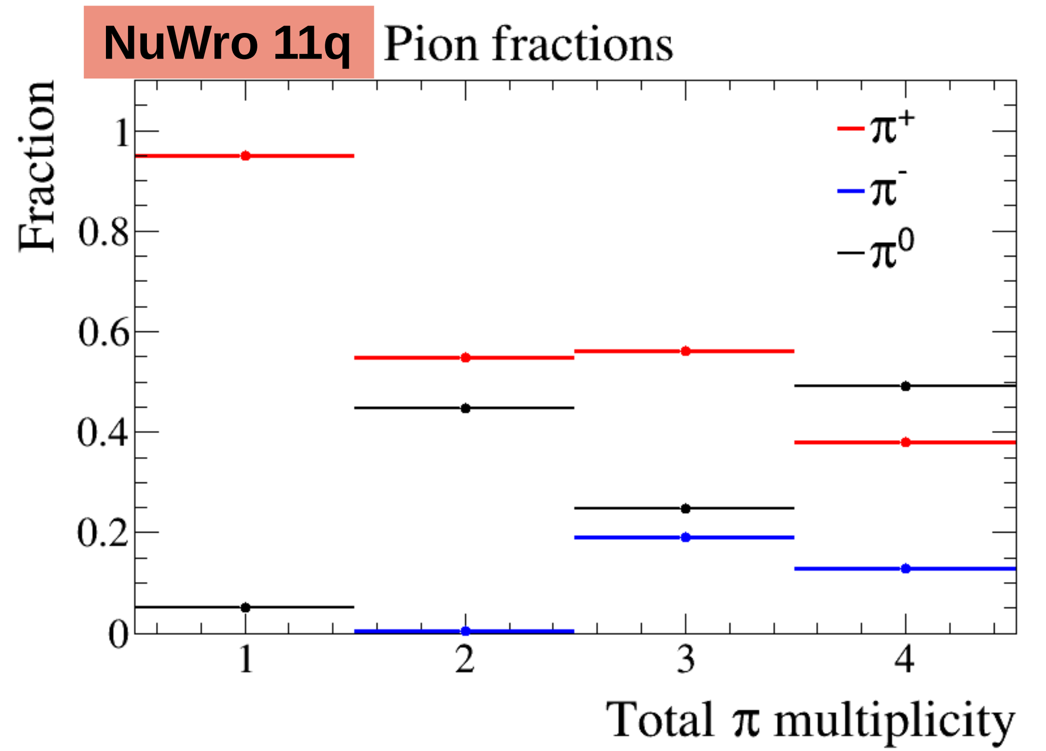
	Efficiency (signal)	Purity
ν_e-like	52.9%	58.4%
$\bar{\nu}_e$-like	71%	27.5%

Phys. Rev. D 97, 072001 (2018)

Multi-pion mode
Hadronic system

- Once number of hadrons is determined, generations of hadronic system is random-based for multi-pion mode:
  - 1 outgoing baryon (50% neutron, 50% proton)
  - remaining hadrons are pions (35% π^+, 35% π^-, 30% π^0)
  - keep the event if charge is balanced, try again else
- Found that obtained pion fractions can be different from what PYTHIA 6 would predict (as seen throught the NuWro predictions)





Old comparison (from NuINT 2015), ν_μ on free protons, no FSI, 1.7<W<2.0 GeV

Summary

- 2 modes producing pions in the resonance region for NEUT 5.4.0:
  - resonant model based on Rein-Sehgal for single pion production
  - custom DIS mode for multi-pion production
- Planning to include MK and DCC models for single pion production in the future
- Multi-pion mode need some work on NC part, and for improved modelization of the hadronic system
- Difficulties when trying to get all the modes together in a coherent way
- Current approach relies on separation between RES and DIS based on multiplicities, but large uncertainties on multiplicity model

BACKUP

Non resonant background
Updates

List of updates NEUT 5.3.4 to 5.4.0:

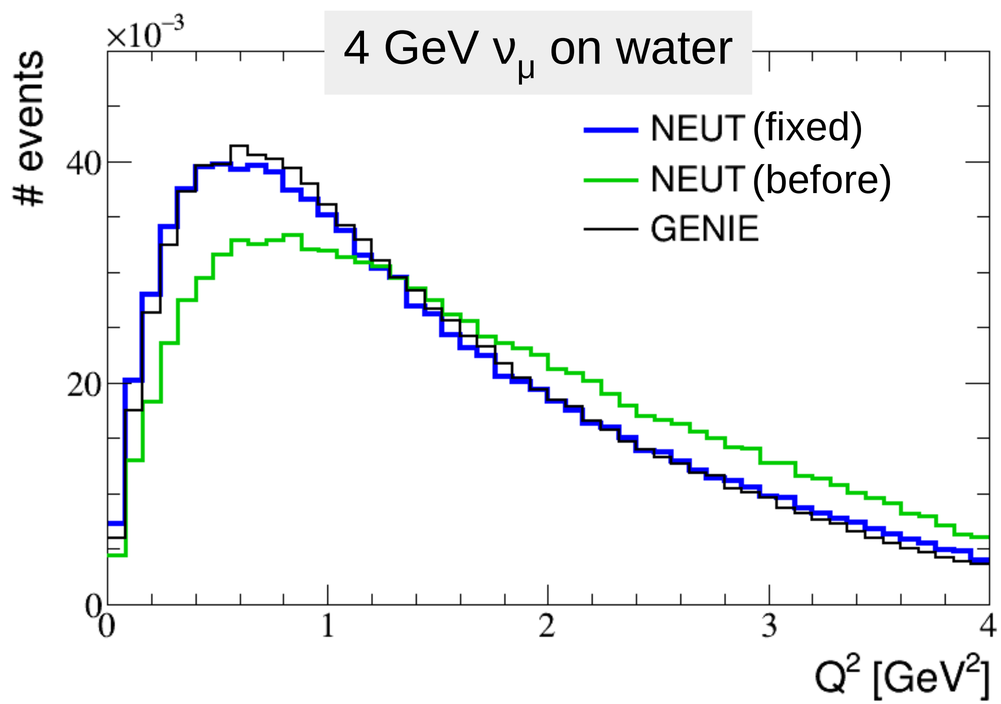
- **Fix relation between Q^2 and x (avoid double counting target mass corrections)**
- Use different cross sections to generate kinematics of interactions on protons and on neutrons
- Fix a typo in the implementation of the Bodek-Yang corrections
- target nucleon is selected based on the ratio of cross-sections on proton and neutron at the interaction energy
- Update version of the Bodek-Yang corrections used hep-ex/0301036 → hep-ph/0508007
- Change the scaling variable to the Nachtmann variable when Bodek-Yang corrections are not used
- Separate structure functions between CC and NC (still need to put the right formula for NC events)
- Use CKM matrix elements when calculating structure functions from PDF
- Added the charm related CKM matrix elements in the calculation of the structure functions if W is large enough to produce charmed particles (enough to produce a proton + a D0)
- Updated values of the CKM matrix elements to PDG 2015
- **Take into account effect of multiplicity on generation of x and y**
- **Added possibility to use different hadron multiplicity model:**
  - current NEUT one (with a small fix of the parameters)
  - my fit of deuterium bubble chamber data
  - AGKY model (used in GENIE)
- Removed passage through a Δ resonance

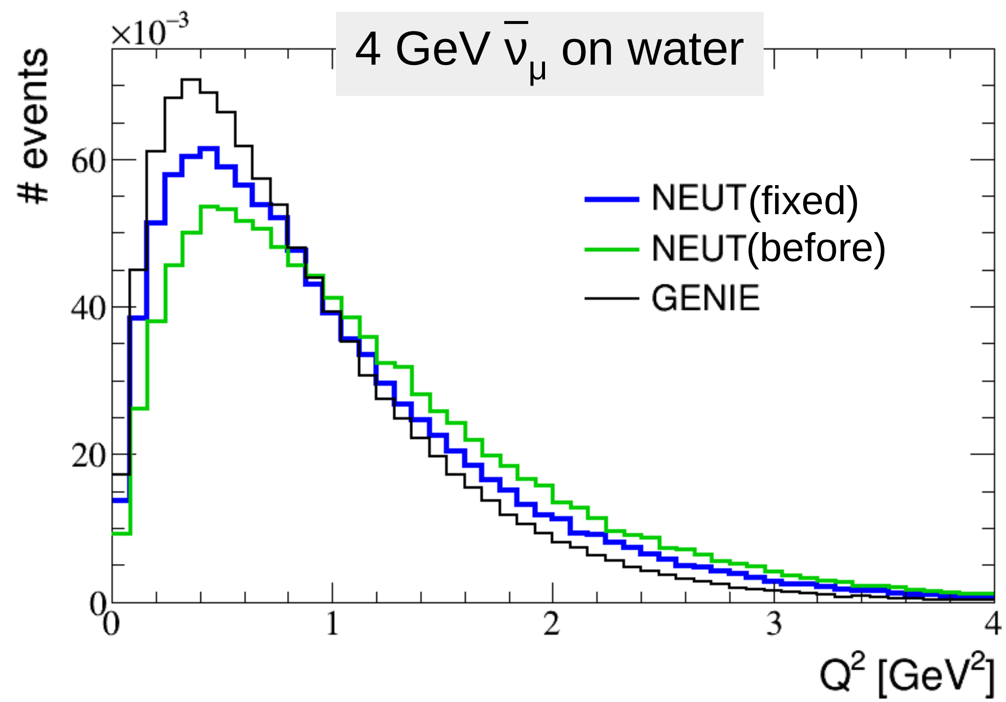
Low W model
Fix relation between x and Q²

- In the NEUT code, the definition of x used to obtain Q² was not the standard one:

$$x = \frac{Q^2}{2M_{nuc}Ey} \quad (1) \qquad \text{but instead:} \qquad x = \frac{Q^2}{2M_{nuc}Ey + M_{nuc}^2} \quad (2)$$

- It seems this is an old definition to take into account target mass effects, but they are already taken into account in corrections by Bodek and Yang
  In 5.3.4, x was generated assuming definition (1) but then (2) was used to deduce Q²





Multiplicity models (Hadronization for low W mode)

- Multiplicity models give the probability to produce a given number of hadrons for a given value of W
- Based on KNO scaling: the distribution of $P(n_{ch})=f(n_{ch}/\langle n_{ch}\rangle)$ is independent of W
- Average charged hadron multiplicity observed to be a linear fonction of $\log(W^2)$ in bubble chamber data
  (K. Kuzmin and V. Naumov argue for a quadratic function at low W in PRC 88, 065501 (2013))

$\langle n_{ch}\rangle = A + B*\log(W^2)$

$P(n_{ch})=f(n_{ch}/\langle n_{ch}\rangle)$

Available energy: W
Neutrino type: $\nu/\bar{\nu}$
Target nucleon: n/p

→

Average charged hadron multiplicity $\langle n_{ch}\rangle$

→

Charged hadron multiplicity probability $P(n_{ch})$

3 or 4 parameters for each couple of neutrino type and target nucleon depending on choice of f